Maximum FRP Bar Diameter and Bar Spacing for Crack Control in Flexural Reinforced Concrete Members

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Abstract. During the design of reinforced concrete elements, satisfying serviceability limit state conditions is very important. To simplify the calculations of crack width, for the elements subjected to bending, the EN 1992-1-1 (2013) gives a restriction of bar diameter or bar spacing which satisfy allowable crack width (tables 7.2(N) and 7.3(N)). During the last decades, FRP reinforcement became a good replacement for steel reinforcement, especially in an aggressive environment. Calculation methods for reinforced concrete elements with FRP bars (FRPRC) are developed from calculation methods for reinforced concrete elements with steel bars. Now, more and more, these rules are implemented in some national codes, and they will be implemented in Eurocodes soon. Procedures for the calculation of maximum bar diameter and bar spacing to control crack width are shown in the paper. These two values depend on each other and the focus of the paper is set on calculations of the bar diameter. Due to different modulus of elasticity between FRP and steel, the tables used for steel cannot be used for concrete beams reinforced with FRP bars. Therefore, the parametric calculations of maximum FRP bar diameter are described in this paper and new tables and diagrams are shown. The calculations were made according to rules from EN 1992-1-1 (2013), paragraph 7.3.4 and Eqs. (7.8) and (7.9) but instead of the material properties for steel reinforcement, those for FRP reinforcement are used. For additional explanations and considerations, EC2 Commentary (2008) is used. Also, due to many types of FRP reinforcement, one table for different materials will not be sufficient. Therefore, for easier usage, diagrams for maximum value of bar diameter are developed and shown in the paper.

Keywords: FRP · Reinforcement · Cracks · Bar diameter · Bar spacing

1 Introduction

Besides satisfying ultimate limit state during the design of reinforced concrete elements, satisfying serviceability limit state conditions is also very important. For elements reinforced with FRP bars satisfying serviceability limit state conditions could be a major issue. To simplify the calculations of crack width, for the elements subjected to bending, the EN 1992-1-1 (2013) gives a restriction of bar diameter (table 7.2(N)) or bar spacing

A. Ilki et al. (Eds.): CICE 2021, LNCE 198, pp. 621–631, 2022.
https://doi.org/10.1007/978-3-030-88166-5_53

(table 7.3(N)) which satisfy allowable crack width. For load-induced cracking the crack width of the element will be less than its maximum permissible value if the conditions either from Table 7.2(N) or Table 7.3(N) are satisfied. On the other hand, if the cracking of the element is caused by restrained imposed deformations, only conditions from Table 7.2(N) should be satisfied (EN 1992-1-1 (2013); Narayanan et al. (2009)). In numerous literature expressions for calculations of the bar diameter or bar spacing limits are given. Corres Peiretti et al. (2003) gives calculations according to Model Code 90, ENV 1992-1-1, and EN 1992-1-1. Similar explanations are given in Eurocode 2 – Commentary (2008).

During the last decades, FRP reinforcement became a good replacement for steel reinforcement especially in an aggressive environment. Calculation methods for reinforced concrete elements with FRP bars are developed from calculation methods for reinforced concrete elements with steel bars. Now, more and more, these rules are implemented in some national codes, and they will be implemented in Eurocodes soon.

Due to different modulus of elasticity between FRP and steel, the tables 7.2(N) and 7.3(N), from EN 1992-1-1 (2013), used for steel cannot be used in calculations for concrete beams reinforced with FRP bars. Therefore, the parametric calculations for FRP reinforcement are described in this paper and new tables and diagrams are shown. The calculations were made according to rules from EN 1992-1-1 (2013), paragraph 7.3.4 and Eqs. (7.8) and (7.9) but instead of the material properties for steel reinforcement, those for FRP reinforcement are used.

2 Cracking Control Without Direct Calculation

According to EN 1992-1-1 (2013) the design crack width can be determined from the following equation:

$$w_{\mathrm{k}} = s_{\mathrm{r,max}} \cdot (\varepsilon_{\mathrm{sm}} - \varepsilon_{\mathrm{cm}}) \tag{1}$$

Where, $s_{\mathrm{r,max}}$ is the maximum crack spacing, and $(\varepsilon_{\mathrm{sm}} - \varepsilon_{\mathrm{cm}})$ is the difference between mean strain in the reinforcement and mean strain of concrete at the level of reinforcement between cracks.

Maximum crack spacing, when the spacing between mean reinforcement is smaller than $5(c + \phi/2)$ is:

$$s_{\mathrm{r,max}} = k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \phi / \rho_{\mathrm{p,eff}} \tag{2}$$

Where c is the concrete cover which is, in this paper, taken as $c = 25$ mm, ϕ is the bar diameter, and the coefficients used are defined with values: $k_1 = 0.8$ (for high bond bars), $k_2 = 0.5$ (for bending), $k_3 = 3.4$, $k_4 = 0.425$.

The expressions for maximum bar diameter and distance between bars that satisfy the maximum crack width are derived from Eqs. (1) and (2) if the following assumptions are considered.

The reinforcement ratio $\rho_{\mathrm{p,eff}}$ is taken as a minimum value and it is derived from expression:

$$\rho_{\mathrm{p,eff}} = \frac{A_{\mathrm{s}}}{A_{\mathrm{c,eff}}} = \frac{k_c \cdot f_{\mathrm{ct,eff}} \cdot \frac{A_{\mathrm{ct}}}{\sigma_{\mathrm{s}}}}{b \cdot 2.5 \cdot (h - d)} \tag{3}$$

The reinforcement area A_s is needed for carrying the bending moment when the first crack appears. This assumption is on the safe side which is shown later in this paper. Value $f_{ct,eff}$ is the mean value of the tensile strength of the concrete, effective at the time when the cracks may first be expected to occur. Area $A_{ct} = b{\cdot}h/2$ is the area of cross section in tension before the appearance of the first crack. Area $A_{c,eff}$ is the effective tension area of cracked cross section.

If it is assumed that $d = 0.9{\cdot}h$ and $k_c = 0.4$ (for bending) then the reinforcement ratio $\rho_{p,eff}$ is:

$$\rho_{p,eff} = \frac{0.8 \cdot f_{ct,eff}}{\sigma_s} \tag{4}$$

So, the maximum crack spacing can be rewritten as:

$$s_{r,max} = 3.4 \cdot 25 + 0.8 \cdot 0.5 \cdot 0.425 \cdot \phi / \rho_{p,eff} = 85 + 0.2125 \cdot \phi \cdot \frac{\sigma_s}{f_{ct,eff}} \tag{5}$$

The difference between mean strain in reinforcement and mean strain of concrete between cracks, according to Model Code 90 (Corres Peiretti et al. (2003)) is:

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s}{E_s} \cdot \left(1 - k_t \cdot \left(\frac{\sigma_{sr}}{\sigma_s}\right)\right) \tag{6}$$

This is the same equation as in EN 1992-1-1 (2013.). Stress in reinforcement for cracking moment can be rewritten from Eq. (3):

$$\sigma_{sr} = \frac{k_c \cdot f_{ct,eff} \cdot h}{5 \cdot (h - d) \cdot \rho_{p,eff}} \tag{7}$$

With Eq. (7), (4) and assumptions that $d = 0.9{\cdot}h$, $k_c = 0.4$ (for bending) and $k_t = 0.4$ (for long term loading), Eq. (6) can be rewritten as:

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s}{E_s} - 0.32 \cdot \frac{f_{ct,eff}}{0.8 \cdot \frac{f_{ct,eff}}{\sigma_s} \cdot E_s} = \frac{\sigma_s}{E_s} - 0.32 \cdot \frac{\sigma_s}{0.8 \cdot E_s} = \frac{\sigma_s}{E_s} - 0.4 \cdot \frac{\sigma_s}{E_s} = 0.6 \cdot \frac{\sigma_s}{E_s} \tag{8}$$

Inserting the values from Eqs. (5) and (8) into (1) and rearranging it, limit value for bar diameter is:

$$\phi = \frac{f_{ct,eff} \cdot E_s \cdot w_k - 51 \cdot \sigma_s \cdot f_{ct,eff}}{0.1275 \cdot \sigma_s^2} \tag{9}$$

The distance between bars is directly connected with bar spacing through the next equation:

$$\rho_{p,eff} = \frac{A_s}{A_{c,eff}} = \frac{\frac{\phi^2 \cdot \pi}{4} \cdot \frac{b}{s_{b,max}}}{b \cdot 2.5 \cdot (h - d)} \tag{10}$$

With assumption from Eq. (4) and that $d = 0.9{\cdot}h$, after rearranging Eq. (10), the maximum bar spacing is:

$$s_{b,max} = \frac{\phi^2 \cdot \pi}{\rho_{p,eff} \cdot h} = \frac{\phi^2 \cdot \pi \cdot \sigma_s}{0.8 \cdot f_{ct,eff} \cdot h} \tag{11}$$

The last equation shows that maximum bar spacing depends on the bar diameter, stress in reinforcement and former assumptions, but also on height of a cross section. From the EN 1992-1-1 (2013) and other background documents it is not clear which amount of height of a cross section is used for calculations of the values in table 7.3(N) from EN 1992-1-1 (2013). Considering that either one of the terms for element subjected to bending should be fulfilled (either bar diameter or bar distance) and bar distance is directly linked to bar diameter, further analysis will regard only bar diameter.

Values from table 7.2(N) from EN 1992-1-1 (2013) are a little bit different than ones calculated by Eq. (9). These values are smaller than theoretical ones, taken to match existing diameters of bars on the market and they are generally conservative. The comparison between the values from EN 1992-1-1 (2013) and theoretical ones is shown in Table 1 and in Fig. 1.

Table 1. Comparison of theoretical values and values from EN 1992-1-1 (2013)

σ_s (N/mm^2)	EN ϕ (mm)	Theoretical ϕ (mm)
160	32	46
200	25	28
240	16	19
280	12	13
320	10	10
360	8	7
400	6	6
450	5	4

Due to an assumptions that $d = 0.9{\cdot}h$, $k_c = 0.4$, $f_{ct,eff} = 2.9$ N/mm^2 and that pure bending is considered, values from table 7.2 (N) should be multiplied with the following coefficients if a different concrete class and other values are used in calculations:

For cross section partially in compression:

$$\frac{f_{ct,eff}}{2.9} \cdot \frac{k_c \cdot h_{cr}}{2 \cdot (h - d)} \tag{12}$$

For cross section in tension:

$$\frac{f_{ct,eff}}{2.9} \cdot \frac{k_c \cdot h_{cr}}{4 \cdot (h - d)} \tag{13}$$

If Eq. (9) is used for calculation, then only second part of coefficients (12) and (13) should be used, because $f_{ct,eff}$ is already included in Eq. (9).

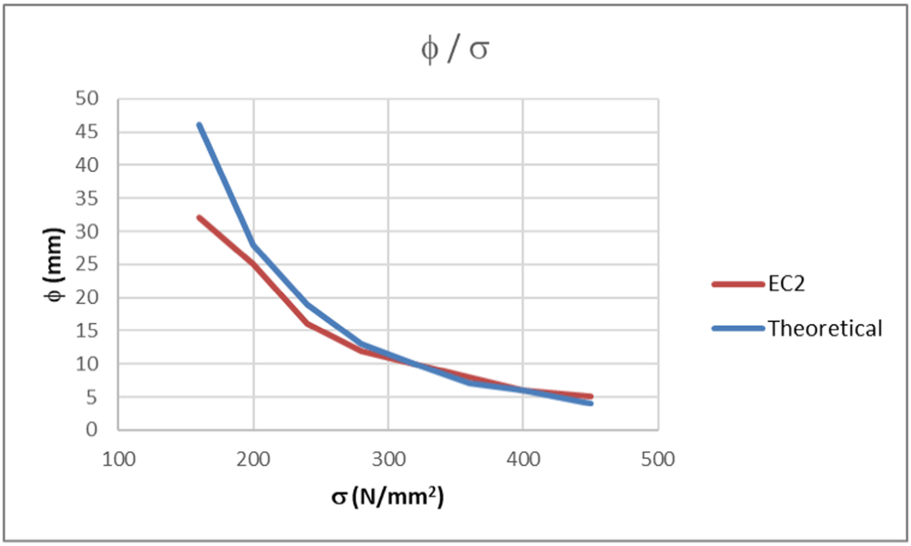

Fig. 1. Comparison of theoretical values and values from EN 1992-1-1 (2013)

3 Cracking Control of FRPRC Elements

Using FRP reinforcement in concrete elements has become more and more usual for specific types of elements, for example, elements in maritime environment, due to good behavior of FRP bars against corrosion. Besides the fact that FRP reinforcement does not corrode, it has other good characteristics such as: high tensile strength, good behavior under dynamic loadings, little relaxation, moisture resistance, and low weight. It is magnetically resistant and an electric isolator. Main deficiencies of FRP when compared to steel reinforcement are their non-ductile behavior and creep rupture (failure due to loss of bearing capacity under long term loadings). In general, FRP bars have lower modulus of elasticity than steel reinforcement and lower coefficient of thermal expansion. FRP reinforcement can be damaged by bending and it is sensitive to ultraviolet exposure.

The calculation procedures of such elements are like procedures for elements with steel reinforcement, but designers should keep in mind non ductile behavior of FRP bars. Ductility of bars is important for satisfying ultimate limit state (for steel reinforcement). For cracking control, the same procedures could be used for both materials because both, steel and FRP reinforcement behave elastic in serviceability limit state.

Due to different modulus of elasticity between FRP and steel, the tables 7.2(N) and 7.3(N), from EN 1992-1-1 (2013), used for steel cannot be used in calculations for concrete beams reinforced with FRP bars. Modulus of elasticity for FRP bars can vary from 35 GPa to 580 GPa. So, for each modulus a different value for maximum bar diameter can be calculated depending on stress in reinforcement.

Maximum bar diameters according to Eq. (9) are calculated for the same stresses as for steel reinforcement. For smaller modulus of elasticity than 200 GPa, maximum bar diameter values were smaller than ones for steel reinforcement, even negative values occurred. Therefore, the calculation was conducted backwards.

From the same values of maximum diameters for steel reinforcement, stresses in FRP were calculated for different values of modulus of elasticity of FRP bars. Further calculations are made with values of diameters from table 7.2(N) from EN 1992-1-1 (2013)

The results are shown in Table 2 and in Fig. 2. Concrete class C30/37 was used, and all assumptions mentioned earlier.

Table 2. Results of analysis – stresses in FRP reinforcement for maximum value of bar diameter

ϕ (mm)	$E = 35$ (GPa) σ_s (N/mm^2)	$E = 50$ (GPa) σ_s (N/mm^2)	$E = 100$ (GPa) σ_s (N/mm^2)	$E = 150$ (GPa) σ_s (N/mm^2)	$E = 200$ (GPa) σ_s (N/mm^2)	$E = 300$ (GPa) σ_s (N/mm^2)	$E = 400$ (GPa) σ_s (N/mm^2)	$E = 580$ (GPa) σ_s (N/mm^2)
32	70.15	86.71	129.02	161.64	189.18	235.45	274.49	334.02
25	77.25	95.90	143.63	180.46	211.59	263.89	308.03	375.35
16	91.19	114.21	173.42	219.26	258.04	323.27	378.36	462.42
12	100.79	127.07	194.97	247.69	292.34	367.51	431.03	527.98
10	107.06	135.60	209.58	267.14	315.94	398.15	467.65	573.77
8	114.87	146.37	228.42	292.46	346.84	438.52	516.09	634.58
6	125.03	160.64	254.15	327.52	389.95	495.38	584.69	721.23
5	131.43	169.82	271.20	351.08	419.16	534.28	631.89	781.21

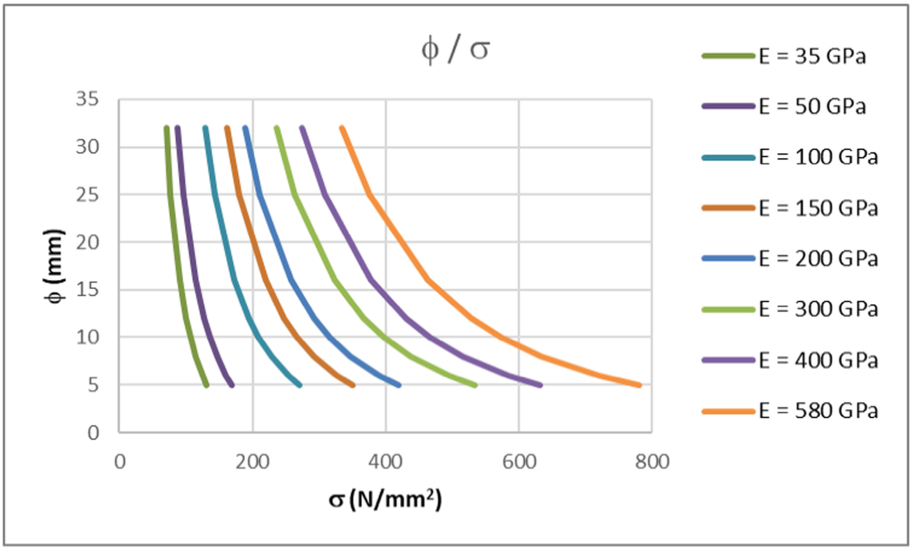

Fig. 2. Ratios of maximum bar diameter and stress in reinforcement for different modulus of elasticity of reinforcement

As can be seen from the Table 2 and Fig. 2, for the same bar diameter, values of stress in reinforcement increases with increasing of modulus of elasticity of reinforcement. Therefore, it is more convenient to calculate stresses in reinforcement from assumed diameter of bar and show the results in form of a diagram for different modulus of elasticity of FRP reinforcement. It should be noted that these curves correspond to calculations using concrete class C30/37 and all earlier mentioned assumptions. If this is not the case the values of maximum bar diameters taken from these curves should be corrected with Eqs. (12) and (13).

4 Parametric Analysis

Due to the complexity of calculation procedures for the estimation of crack width, the calculation procedures were implemented into spreadsheet calculator and Visual Basic for Application procedures (VBA). Besides the crack width calculation, the procedures for bearing capacity and deflection control have also been made. The problem with FRPRC sections is that in most cases ultimate limit state is not governing the design. In most cases reinforcement for bearing capacity is not enough to satisfy the serviceability limit states. The reason for this is the lower modulus of elasticity of most FRP bars comparing to steel. Therefore, all three aspects should be taken into consideration during the design of FRPRC elements.

To verify calculations of maximum bar diameters and to confirm that usage of that limit leads to crack width less than $w_k = 0{,}3$ mm, parametric analysis has been made. The goal was to calculate the stresses in reinforcement of different diameters for different values of bending moment, while the maximum crack width is satisfied. The cross section is a typical slab cross section, 100 cm wide, 20 cm high, with concrete cover $c = 25$ mm, cast from concrete class C30/37. Modulus of elasticity of FRP bars was $E_f = 50000$ N/mm^2. The calculation was made for different bar diameters, from table 7.2(N) from EN 1992-1-1 (2013) First bending moment is equal to the cracking moment of that cross section, which is equal to $M_{cr} = 19.33$ kNm, after which three higher values have been used, $M_{Ed} = 30$ kNm, $M_{Ed} = 40$ kNm and $M_{Ed} = 50$ kNm. The amount of reinforcement in cross section corresponds to area which satisfies characteristic crack width of $w_k = 0.3$ mm for each amount of the bending moments. The results are shown in Table 3 and diagram on Fig. 3.

Table 3. Results of parametric analysis

Calculation ϕ (mm)	$M = M_{cr}$ σ_s (N/mm^2)	$M = 30$ σ_s (N/mm^2)	$M = 40$ σ_s (N/mm^2)	$M = 50$ σ_s (N/mm^2)
32	90.44	103.59	108.81	114.11
25	98.45	112.59	117.25	122.22
16	114.77	130.46	133.60	137.58
12	126.44	142.88	144.63	147.68
10	134.26	151.04	151.71	154.04

(*continued*)

Table 3. (*continued*)

Calculation ϕ (mm)	$M = M_{cr}$ σ_s (N/mm^2)	$M = 30$ σ_s (N/mm^2)	$M = 40$ σ_s (N/mm^2)	$M = 50$ σ_s (N/mm^2)
8	144.21	161.23	160.36	161.68
6	157.54	174.54	171.32	171.14
5	166.20	182.97	178.06	176.82

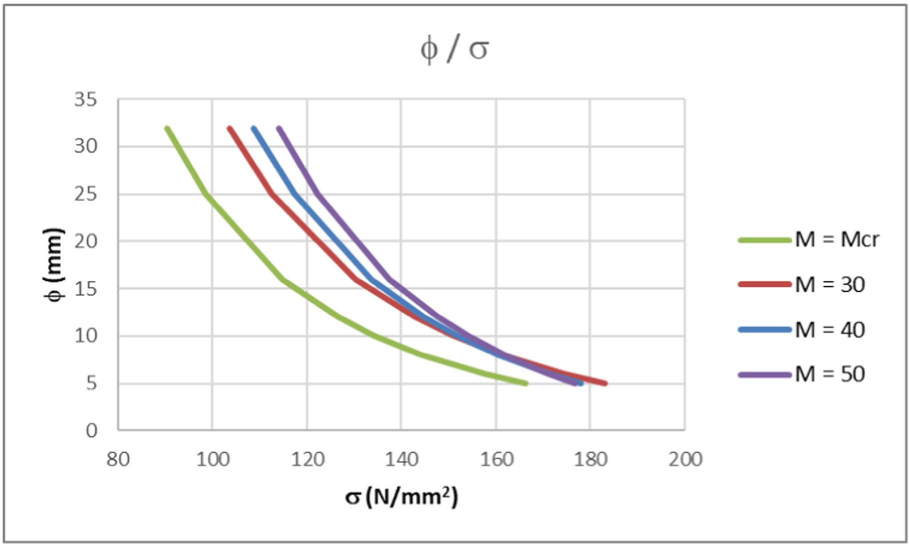

Fig. 3. Results of parametric analysis

With the increase of bending moment, curves ϕ/σ are shifted to the right which means that if the maximum bar diameter is taken according to the curve for $M = M_{cr,}$ the calculation will be on the safe side. For the same stress in reinforcement, maximum bar diameter increases with the increase of bending moment. So, if the chosen bar diameter is lower for certain stress in reinforcement than the bar diameter for $M = M_{cr}$, crack width will be satisfied. That confirms claims from background documents (Eurocode 2, Commentary, (2008) and Corres Peiretti et al. (2003)).

Values of stresses in reinforcement while bending moment is $M = M_{cr}$ should be equal to those from Table 2, concerning adequate modulus of elasticity of FRP reinforcement. For the same input parameters from previous analysis, the calculation of stresses in FRP reinforcement, for $M = M_{cr}$ and for each bar diameter and modulus of elasticity of FRP reinforcement (from the Table 2) is carried out. Calculation was made by the same VBA procedure for calculating crack width. The results are presented in the Table 4. Also, those results are compared with those from Table 2 in the diagram on Fig. 4. Comparison is made for FRP reinforcement with modulus of elasticity range from 35000 N/mm^2 to 200000 N/mm^2.

Table 4. Results of analysis – stresses in reinforcement for maximum bar diameter calculated with VBA procedure for crack width control

ϕ (mm)	$E = 35$ (GPa) σ_s (N/mm^2)	$E = 50$ (GPa) σ_s (N/mm^2)	$E = 100$ (GPa) σ_s (N/mm^2)	$E = 150$ (GPa) σ_s (N/mm^2)	$E = 200$ (GPa) σ_s (N/mm^2)	$E = 300$ (GPa) σ_s (N/mm^2)	$E = 400$ (GPa) σ_s (N/mm^2)	$E = 580$ (GPa) σ_s (N/mm^2)
32	72.42	90.44	137.79	175.42	207.88	263.65	311.82	387.03
25	78.60	98.45	150.65	192.12	227.89	289.34	342.39	425.19
16	91.02	114.77	177.32	227.06	269.93	343.55	407.07	506.13
12	99.76	126.44	196.87	252.92	301.25	384.20	455.74	567.27
10	105.54	134.26	210.21	270.70	322.87	412.42	489.64	609.97
8	112.81	144.21	227.50	293.94	351.26	449.66	534.50	666.68
6	122.39	157.54	251.28	326.27	391.02	502.22	598.10	747.43
5	128.50	166.20	267.14	348.09	418.04	538.23	641.87	803.29

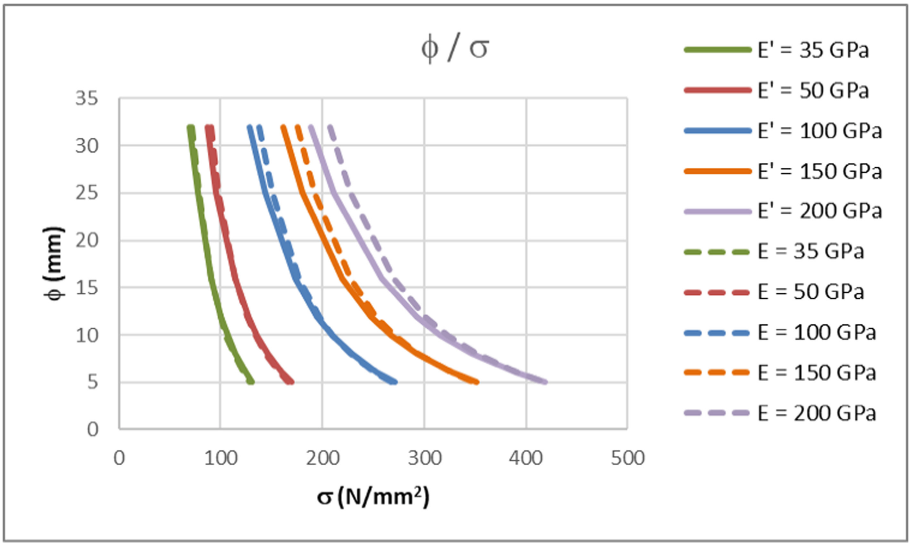

Fig. 4. Results of analysis – stresses in reinforcement for maximum bar diameter calculated with VBA procedure for crack width control

In the diagram in Fig. 4 curves denoted with mark E' are the ones calculated with VBA procedure, and curves mark with E are the ones calculated by simple procedure described in the first chapter. There is little discrepancy between corresponding curves for the same modulus of elasticity. Those differences are greater with the higher value of modulus of elasticity and larger bar diameter. The good thing is that the values from Table 2 are on the safe side which justifies the usage of tables or diagrams for maximum bar diameter.

The reason for such differences lies in the assumptions considered during calculations of values of parameters in tables and diagrams with maximum bar diameter for cracking control.

Those calculations assume that effective depth of cross section is $d = 0.9 \cdot h$, while in exact calculation effective height is taken as $d = h - (c + \phi/2)$. So, if the concrete cover is a fixed value and bar diameter is variable, then d/h ratio is also a variable value. Also, the lever arm z for calculation of stress in reinforcement is assumed as $z = 0.8 \cdot h$, while in exact calculation it is calculated from geometrical properties of cracked cross section. Effective height of concrete in tension is assumed to be $h_{\text{eff}} = 2.5 \cdot (h - d)$ which is not always the case. In previous parametric analysis that value was taken as $(h - x)/3$ which was the smaller value. All these little differences led to differences in results but on the safe side. It should be noted that this analysis is carried out for cross section height of $h = 20$ cm which can be the height of a typical floor slab. If a thicker slab was used the results would be different, especially because of the way of calculating effective height in exact calculation.

5 Conclusions

Concrete members reinforced with FRP are sensitive to serviceability limit states. Even when the ultimate limit state is satisfied, crack width and/or deflections could be the problem. Calculation procedures for cracking control of steel reinforced concrete elements could be used for elements with FRP reinforcement, regarding to different modulus of elasticity of reinforcement. This is possible because steel reinforcement is also in the elastic region considering serviceability limit state.

To simplify the calculations of crack width, for the elements subjected to bending, the EN 1992-1-1 (2013) gives a restriction of bar diameter (table 7.2(N)) or bar spacing (table 7.3(N)) which satisfy allowable crack width. For load-induced cracking the crack width of the element will be satisfied if the condition either from Table 7.2(N) or Table 7.3(N) are satisfied, while, if the cracking of element is due to restrained imposed deformations, conditions from Table 7.2(N) should be satisfied.

Due to different modulus of elasticity between FRP and steel, the tables 7.2(N) and 7.3(N), from EN 1992-1-1, used for steel cannot be used in calculations for concrete beams reinforced with FRP bars.

Modulus of elasticity for FRP bar can vary, from 35 GPa to 580 GPa.

In this paper, for each modulus of elasticity of FRP reinforcement and for a different value of maximum bar diameter, stresses in reinforcement have been calculated. The procedure is conducted backwards because the range of stresses in steel reinforcement is not equal to the range of stresses in FRP reinforcement and usage of stresses for steel reinforcement led to very small bar diameters and even to negative values.

The values of maximum bar diameter for satisfying crack width have been shown in Table 2 and diagram on Fig. 2.

To check these values, parametric analysis has been made. The procedures for calculating crack width for certain cross section, type of reinforcement and bending moment have been made in VBA. Also, that procedure can be used to find the exact amount of reinforcement needed to satisfy characteristic crack width. These procedures were very useful in those analysis.

The conclusion is that diagrams for maximum bar diameters for different modulus of elasticity of FRP reinforcement, could be useful for fast control of cracking in concrete elements reinforced with FRP reinforcement. These curves are on the safe side comparing to the exact calculations. Some assumptions taken in calculations of diagrams could be a little different than the values taken into exact calculation of the crack width.

In this paper, all analyses were made just for concrete class C30/37. For other concrete classes, if diagrams from this paper are used, the values of bar diameters should be used with correction factors.

Acknowledgment. The authors wish to acknowledge financial support granted in the scope of short-term scientific support from University of Zagreb.

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